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## Chandra X-ray Observations of WZ Sge in Superoutburst

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**Abstract.** We present seven separate *Chandra* observations of the 2001 superoutburst of WZ Sge. The high-energy outburst was dominated by intense EUV emission lines, which we interpret as boundary layer emission scattered into our line of sight in an accretion disc wind. The direct boundary layer emission was hidden from view, presumably by the accretion disc. The optical *outburst orbital hump* was detected in the EUV, but the *common superhump* was not, indicating a geometric mechanism in the former and a dissipative mechanism in the latter. X-rays detected during outburst were not consistent with boundary layer emission and we argue that there must be a second source of X-rays in dwarf novae in outburst.

### 1. Introduction

WZ Sge is a nearby, short period dwarf nova with an exceptionally long inter-outburst interval (20–30 yr). These long intervals are probably caused by the truncation of the (usually unstable) inner accretion disc by the magnetic field of the white dwarf (Warner, Livio, & Tout 1996; Hameury, Lasota, & Hure 1997). This picture is supported by the detection of a 28 s modulation in the quiescent optical and X-ray emission, which is probably the spin period of the magnetised white dwarf (Patterson, Richman, Kemp, & Mukai 1998).

The July–August 2001 superoutburst of WZ Sge was the first since 1978, and was observed intensively from the ground and from space (e.g., Patterson et al. 2002; Knigge et al. 2002; Long et al. 2003; Sion et al. 2003). In this paper we present the X-ray and extreme-ultraviolet (EUV) observations made with the *Chandra* observatory. These data were originally reported by Wheatley et al. (2001) and Kuulkers et al. (2002).

### 2. Observations

WZ Sge was observed seven times with *Chandra* during the 2001 superoutburst. Three observations were made using the Low Energy Transmission Grating (LETG) and four with the Advanced CCD Imaging Spectrometer (ACIS-S). LETG observations provide high spectral resolution in the EUV and soft X-ray wavebands (5–170 Å). ACIS-S provides low-resolution observations in the hard and soft X-ray wavebands (1–50 Å). The times of all seven observations are indicated with respect to the optical outburst in the top panel of Fig. 1. The LETG observations are identified with the labels L1–3 and the ACIS-S observations with A1–4.

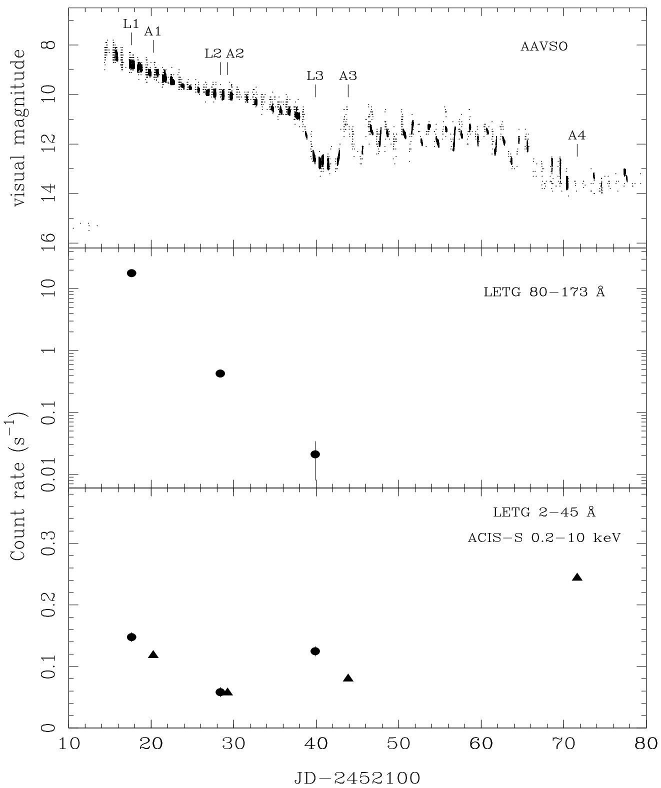


Figure 1. Optical, EUV, and X-ray light curves of the 2001 superoutburst of WZ Sge. Top: the AAVSO visual light curve. Middle: the *Chandra* LETG 80–173 Å EUV light curve plotted on the same dynamic range as the visual light curve. Bottom: the *Chandra* LETG 2–45 Å X-ray light curve (circles) and the ACIS-S 0.2–10 keV X-ray light curve (triangles). The ACIS-S count rates have been scaled by a factor 1/17 in order to align the A2 and L2 count rates. The times of the *Chandra* observations are labelled on the AAVSO panel, with L indicating a LETG observation and A indicating an ACIS-S observation.

## 3. Light curves

The lower panels of Fig. 1 show the mean count rates from the seven *Chandra* observations. It can be seen that the EUV flux was very high in the early outburst and then declined more quickly than the optical. The X-ray flux dropped gradually during the main outburst, recovered after the end of the main outburst (L3), but was suppressed again during the first echo outburst (A3). The X-ray flux recovered again (by a larger factor) by the end of the echo outbursts (A4). This overall EUV and X-ray flux evolution is broadly consistent with that seen in other dwarf novae in outburst (e.g., Wheatley, Mauche, & Mattei 2003).

Light curves from the first 11 d of the optical outburst were dominated by an *outburst orbital hump* (OOH; Patterson et al. 2002). This is believed to be due to the excitation of the 2:1 tidal resonance in the expanding accretion disc, and is seen only in WZ Sge-type stars, where the mass ratio is sufficiently extreme to allow the disc to reach the resonant radius (Osaki & Meyer 2002; Kato 2002). The later optical outburst is dominated by the *common superhump,* which is a

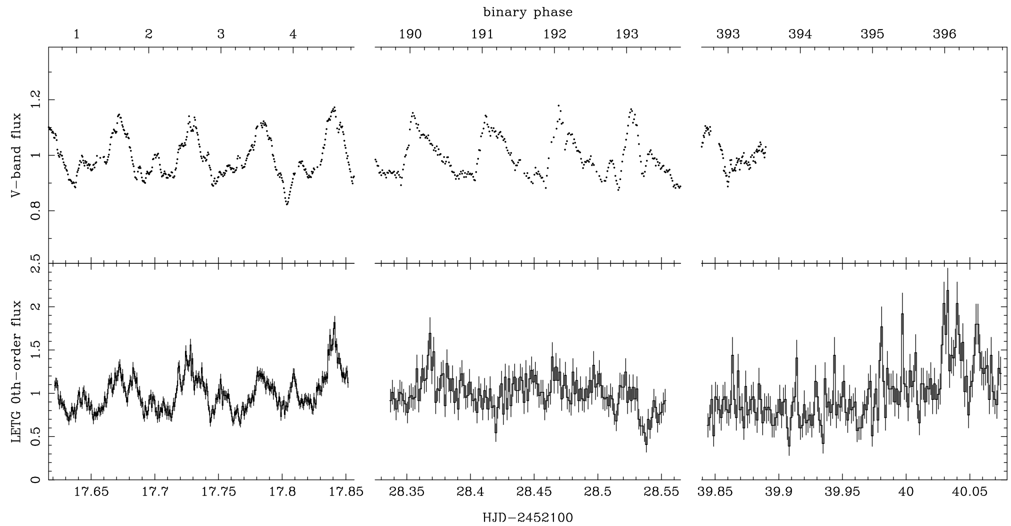


Figure 2. Optical and *Chandra* LETG light curves from observations L1–3. Top: optical light curve in flux units $10^{-0.4(V-C)}$, where $V$ ($C$) is WZ Sge's (the comparison star's) visual magnitude, normalised to one over the interval of overlap with the LETG data. Bottom: LETG 0th-order light curve binned at 64 s (L1) and 128 s (L2 and L3) and normalised to one in each observation. Optical data were originally presented by Patterson et al. (2002).

feature of the superoutbursts in all dwarf novae, and is believed to be due to the excitation of the 3:1 tidal resonance.

The light curves of the individual LETG observations, plotted in Fig. 2, show that the OOH is detected in the EUV, but that the common superhump is not. It can seen that the OOH modulations in the optical and EUV are both double peaked and in phase. These results suggest that the OOH is a geometric effect, with a two-arm spiral wave modifying our view of the inner accretion disc and/or white dwarf. The absence of the common superhump in the EUV emission supports the view that this is a dissipative effect in the eccentric accretion disc.

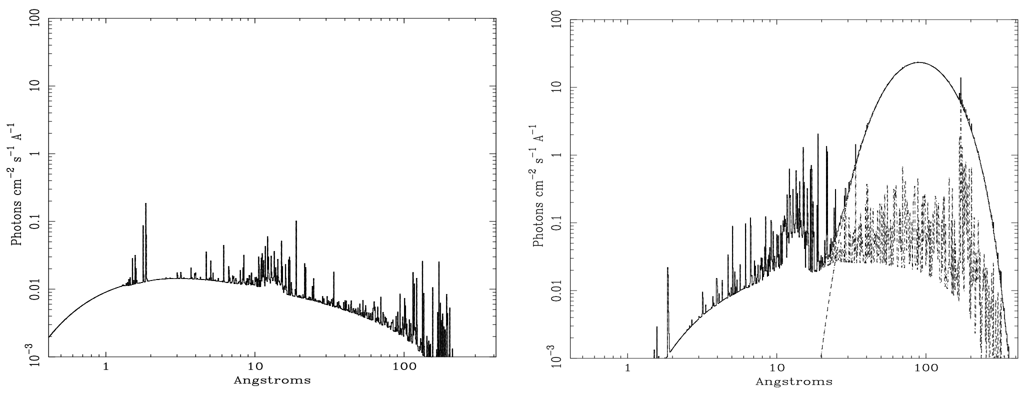


Figure 3. Schematic X-ray spectra of dwarf novae in quiescence (left) and outburst (right).

## 4. Spectra

The high-energy spectra of dwarf novae change dramatically between quiescence and outburst. This is illustrated in Fig. 3. Quiescent X-ray spectra are normally fitted with multi-temperature optically thin thermal models, such as cooling flows, with temperatures in the range 1–10 keV (e.g., Mukai et al. 2003). In outburst the X-ray emission is replaced with intense optically thick emission in the EUV band, with characteristic temperatures around 10 eV (e.g., Mauche 2004), and an X-ray spectrum that is lower in temperature than in quiescence (e.g., Baskill, Wheatley, & Osborne 2004).

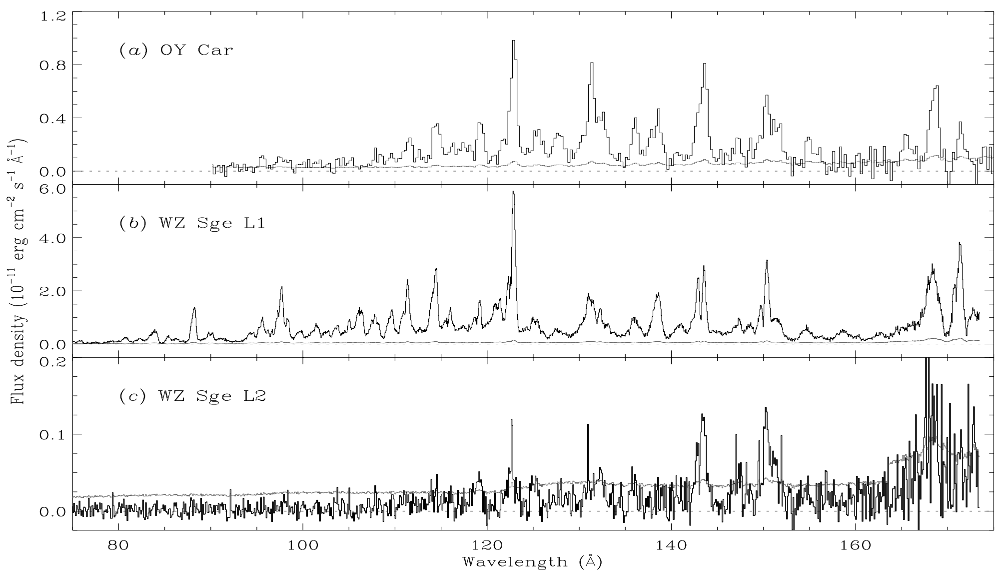


Figure 4. *EUVE* SW spectrum of OY Car in superoutburst ($a$) and *Chandra* LETG spectra of WZ Sge from observations L1 ($b$) and L2 ($c$). Data are binned at 0.25, 0.05, and 0.1 Å, respectively. Grey histograms are the associated $1\,\sigma$ error vectors. *EUVE* data were originally presented by Mauche & Raymond (2000).

The L1 and L2 EUV spectra of WZ Sge in outburst are plotted in the lower panels of Fig. 4. Instead of the expected bright continuum these spectra are dominated by strong and broad emission lines. The only similar EUV spectrum of a dwarf nova is the *EUVE* spectrum of the eclipsing system OY Car in superoutburst, which is reproduced in the top panel of Fig. 4. The similarity is striking. Mauche & Raymond (2000) argued that this spectrum can be understood if the boundary layer of OY Car is hidden from direct view by the highly-inclined accretion disk, and if boundary layer radiation is scattered into our line of sight by the accretion disk wind. This interpretation naturally explains the salient features of the EUV spectra of OY Car and WZ Sge in outburst: the lines are identified with resonance transitions of intermediate ionisation stages of cosmically abundant elements, the lines are broad (FWHM $\approx 1\,\text{Å} \sim 3000\,\mathrm{km\,s^{-1}}$) because the wind velocity is high, and the continuum is weak because the wind electron optical depth is low. The inclination of WZ Sge is $77^\circ \pm 2^\circ$ (Spruit &

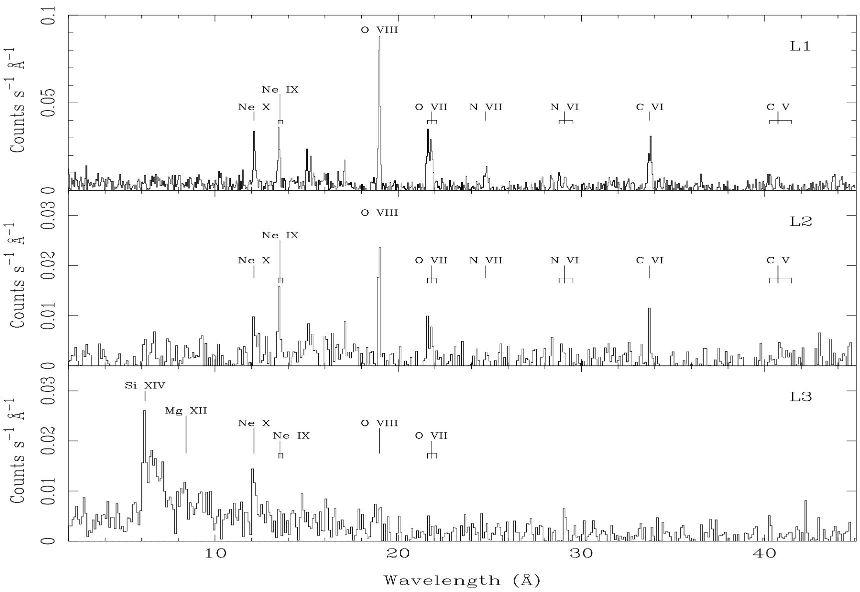


Figure 5. The short-wavelength LETG spectra from all three observations (L1–3). The X-ray spectrum in the first two observations is dominated by emission lines from H-like and He-like species of C, N, O, Ne. These are labelled. Other lines include those of the Fe L-shell (15–18 Å). The third spectrum also contains thermal lines, but the line ratios (e.g., Ne) show that the temperatures are much higher.

Rutten 1998) and so this interpretation requires that optically thick material extends at least 11° out of the orbital plane.

The LETG X-ray spectra during outburst are plotted in Fig. 5. The first two spectra are dominated by emission lines of H- and He-like species of C, N, O, and Ne. These spectra are therefore likely to represent thermal emission from a collisionally-excited optically thin plasma. The third LETG spectrum, taken late in the decline from the main outburst and before the first echo outburst, shows a blue continuum and strong H-like lines (note in particular the reversed H- and He-like line ratios of Ne). This spectrum clearly originates from a plasma that is much hotter than that responsible for the L1 and L2 short-wavelength spectra. Fitting this third spectrum, we find an acceptable fit with a single-temperature thermal plasma model with $kT = 6.0\pm^{4.0}_{1.7}$ keV and $N_{\rm H} = (1.4 \pm 0.5) \times 10^{21}$ cm$^{-2}$. This temperature is typical of the boundary layers of dwarf novae in quiescence, while the high column density is presumably due to the remnants of the disc material that blocked our view of the boundary layer during outburst.

The L1 and L2 spectra, in contrast, are not consistent with emission from the boundary layer. Spectral fitting shows that the emission measure rises to lower temperatures, whereas boundary layer emission in quiescence rises to high temperatures (e.g., Mukai et al. 2003). More importantly, the L1 and L2 spectra are not consistent with the high column density measured in the L3 spectrum. This shows that the X-ray emission seen in outburst cannot pass through the material blocking our view to the boundary layer.

Other possible sources of X-ray emission during outburst include scattering in the accretion disc wind (as we suggest for the EUV component). This has also been suggested to explain the lack of soft X-ray eclipses in high-state systems (e.g., Pratt et al. 2004). However, unlike the EUV, there is no evidence for a strong continuum in soft X-rays that could be scattered by the wind. The soft X-ray lines also arise from more highly ionised species than are believed to be present in the wind, and crucially, the X-ray lines in WZ Sge are too narrow to be due to scattering in the wind ($800\,\mathrm{km\,s^{-1}}$ compared with $3000\,\mathrm{km\,s^{-1}}$ in the EUV).

Alternative possibilities for the origin of soft X-rays during dwarf nova outbursts include internal shocks in the $3000\,\mathrm{km\,s^{-1}}$ wind, and solar-like coronal emission from the atmosphere of the accretion disc itself ($800\,\mathrm{km\,s^{-1}}$ corresponds to the Kepler velocity of the accretion disc at a radius of around $2 \times 10^{10}$ cm). Coronal emission might turn on in outburst as the disc becomes more magnetically active. In this case soft X-ray outburst emission might allow us to study the magneto-rotational instability in action.

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